High-Current Beam Transport Experiments Using Foil Focussing

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Introduction

Numerous applications of electron beams require transport, centering and steering of relativistic, high current electron beams(REB). One method which has application to all of these objectives involves the use of conducting grounded foils transverse to the beam direction.[1,2] This technique allows self-pinched stable transport of high current REB's in vacuum, with currents in excess of the longitudinal space charge limit. Beam centering is accomplished via the image currents in the tube walls which provide a current dependent centering force for the electron beam.

When relativistic electron beams propagate in vacuum, the major forces responsible for the beam envelope properties are the electrostatic defocusing force due to the beam space charge, the focusing force due to the self magnetic field of the beam current and the perpendicular temperature or emittance of the beam. In the case of an infinitely long beam with zero emittance, the forces on the beam are unequal and the electrostatic force exceeds the magnetic force by a factor of $1/\gamma^2$. When a periodic array of transverse conducting foils are placed in the path of the beam the force balance in the beam is modified still further. In the vicinity of the transverse conducting foils, the radial electric field of the beam is shorted out by the foils, leaving the beam's self-magnetic field to pinch the beam to a smaller radius. However, between foils the defocusing electrostatic force dominates causing beam expansion. If the foil spacing is chosen properly, the electrostatic and self-magnetic forces can be balanced in an average sense with the beam maintaining a constant average radius as it propagates through a periodic array of foil cells. Relaxing the assumption of a cold or zero emittance beam does not fundamentally alter the problem, but rather increases the average beam radius for a given beam current and energy. The required foil spacing is a function of the beam energy, current , emittance and radius as well as transport tube wall radius. [1]

The presence of the grounded conducting foils also changes the axial electric field, thereby lowering the beam's space charge potential. This permits currents in excess of the longitudinal space charge limit to propagate through the structure.

Another effect associated with the transverse foils is a weak centering of the beam.[3] The foils reduce the defocusing effect of image charges on the transport tube walls without affecting the return image currents. Thus any asymmetries in the return currents due to the beam displacement off the axis result in a net centering force on the beam. In addition, as ref. 1 and 2 show, the foils give rise to an anharmonic potential well near the ends of each cell in the transport system that extends to the inside of the beam, resulting in a spread of the betatron oscillation frequencies for the beam electrons. This helps to stabilize the beam against transverse instabilities, such as the resistive hose.[4]

Experiments

NRL's SuperIBEX[5] high energy electron accelerator has been operational since the Fall of 1988. SuperIBEX is a 5.5 MV, 100 kA device, with a 40 nsec full width at half maximum. It consists of 3 major components : a 49 stage Marx generator, an intermediate storage capacitor and a pulse forming network (PFN). At peak charge, the Marx generator produces a 2.6 MV output pulse with 1 μsec risetime. The pulse charges a 6 nF coaxial water capacitor, until an adjustable oil output switch fires charging the SuperIBEX PFN. The PFN consists of a triaxial system where both sides of the intermediate storage capacitor are charged simultaneously. Six oil switches are set to self-break when the line is fully charged sending the pulse to the diode. The diode pulse has a 10-nsec risetime with 30-nsec flattop and 10-nsec fall time with essentially no prepulse.

In the past several months experiments have been performed to determine the transport properties of tranverse grounded conducting foils on the output beam from SuperIBEX. The experiments were performed with a nominal beam energy of 4.5 MeV and currents in the 5-45 kA range. The remainder of the diode current was scraped off by the anode structure and a series of range-thick graphite apertures located immediately downstream of the anode.

Figure 1 shows a schematic diagram of the foil transport experiment. Control of the output current was obtained by using carbon apertures of different diameters. Two different configurations of transverse foils were used in the experiments reported here. Most of the data was taken with thin wire grids which consisted of 4-mil stainless steel wire strung in a 5-mm grid pattern across a 10-cm diameter drift tube. The wire grids are electrically equivalent to solid conducting foils, however unlike solid foils the grids do not heat the beam due to scattering as much. In some cases, the 5-mm square grid pattern was replaced by two 4-mil stainless steel wires strung across the tube in a cross-hair configuration. The cross-hairs were designed to provide additional centering for the beam by using the electrostatic image charge induced on the wires and the axial symmetry imposed by the cross.

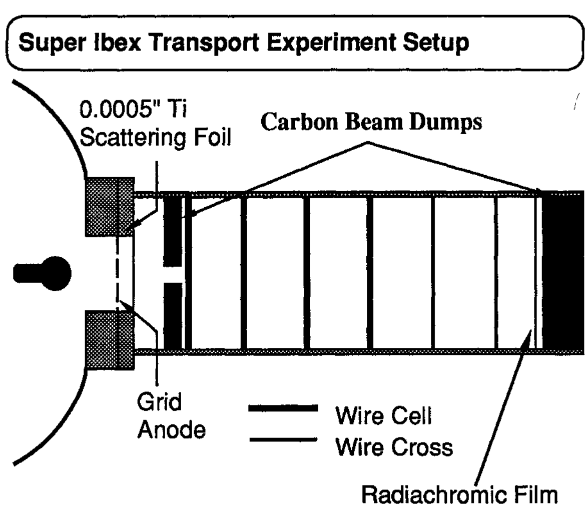

Figure 1 : SuperIBEX Foil and Cross Transport Experiment .

Results and Discussion

One important property of a foil transport system is its beam current transport efficiency. In the following discussion, transport efficiency denotes the ratio of the peak beam currents at the entrance to thatat the exit of the transport system, regardless of its effects on beam emittance or cross section.

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One of the parameters that affect the transport efficiency is the cell spacing. The matched cell length, as described above, is the length for which the beam maintains a constant average radius as it passes through the transport section. Figure 2 shows the results of an experiment designed to measure the transport efficiency of a foil focusing system as a function of the cell length (the distance between two consecutive foils). The cell length for this experiment was varied above and below the theoretical matched cell condition. The nominal injected beam current was 20 kA. A range thick carbon aperture, 1.2 cm in diameter was located 5 cm downstream of the anode, resulting in an input beam 0.6 cm in radius. The typical injected beam energy was 4 - 4.5 MeV. The transport tube was a 50-cm long stainless steel tube, 10 cm in diameter. The predicted length for the matched cell for these beam parameters is 6 cm .[1]

Figure 2 shows that for cell lengths equal to or less than the theoretically-predicted matched condition cell-length of 6 cm, 100% beam current transport is observed for the entire 50 cm tube. In addition, time integrated measurements of the beam cross section at the input and output of the transport cell indicate that the beam remains reasonably well centered without dramatic changes in beam radius subsequent to the transport cell. By contrast for cell lengths larger than the matched condition cell-spacing we observed a very rapid degradation of the transport efficiency. Less than 50% of the total current was transported through the transport section using foil cell spacings only slightly less than twice the matched cell length spacing. When the wire grid transport array was removed from the interior of the tube, the current measured 50 cm downstream from the anode was < 4 kA. This puts a lower limit on the beam emittance of 0.15 cm-rad assuming self-similar beam expansion for a fully unneutralized beam.

Since the longitudinal space charge limited current for this tube was approximately 30 kA[7] and the injected current was approximately 20 kA, the loss of beam current cannot be attributed to this effect. With the foils in place currents as high as 45 kA have been propagated, which exceeds the longitudinal space charge limit by a significant margin for a 4.5 MeV electron beam.

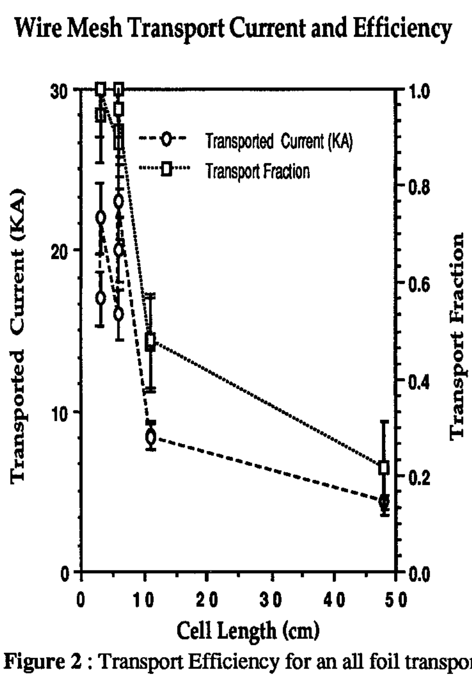

Figure 2 : Transport Efficiency for an all foil transport system

Figure 3 shows the results of a series of experiments in which the foil cell length was held constant at 6 cm, the transport section length was 36 cm and the injected beam current was varied from 10 to 33 kA. The results are similar to the previous case, with 100% efficiency observed for all currents up to 33 kA. The efficiency drops slowly for currents above this value, approaching 80% for an input current of 55 kA. Another series of experiments with 3 cm long cells, which would be matched to 60 kA, also showed a similar fall-off of efficiency above 40 kA.

At least two explanations of the observed fall-off of transport efficiency with current are possible. Either high input beam emittance or emittance growth during transport can significantly lower the transport efficiency of the foil system. First the input beam current was controlled with a range thick carbon aperture. Larger apertures with higher emittance acceptance were used to increase the current, so that at high currents ransport losses would be expected due to the significantly higher injected beam emittance. Second, the beam emittance growth, as it propagates through the structure, depends on the number of cells, the beam current and the mismatch of the beam to the cell. Each foil represents a non-linear thin lens for the beam which produces a finite emittance growth. Thus as the number of foils traversed increases so does the beam emittance. The amount of emittance growth is also current dependent so that higher current beams suffer much larger emittance growth than the low current beams. The matching of the beam to a particular cell is also important. The farther the beam is from a matched condition, the more emittance growth will occur and the greater the current losses from the beam. Thus as an initially matched beam traverses a foil system it will become increasingly mismatched to the structure and losses will occur. Higher currents accelerate the emittance growth and may result in decreased transport efficiency.

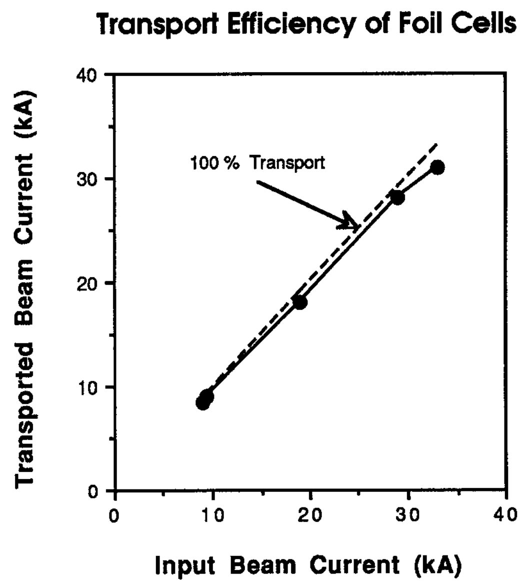

Figure 3: Graph showing the transport efficiency of a periodic foil array for beam currents up to 33 kA, with 6 cells of length 6 cm.

We have also observed a loss of transport efficiency in longer transport systems. When the length of the transport tube is increased from 50 cm to 68 cm, we still observe 100% transport for the first 50 cm, but at 68 cm we observe a drop in efficiency as high as 30% accompanied by a significant increase of the beam cross section. As we pointed out above when a beam passes through a foil transport system its current, emittance and size can change. Thus a matched cell near the entrance may not be matched further downstream. To accommodate the change in beam parameters as the beam passes through the transport system the cell length should be modified. All the cells in our system were identical, resulting in a more severe mismatch as the beam propagated further into it. Recent computational results[8] indicate that such a mismatched beam can deteriorate rapidly within the transport system.

When the last two foils in an 8 cell, 48 cm long foil focusing system were replaced with centered wire crosses, we obtained the results shown in figure 4. For a wide range of input currents, the transport efficiency dropped from 100% in the case of wire grids, to about 70 % with the crosses. When the two cells that contained crosses were replaced with blanks, the transport efficiency decreased to about 50%, as shown in figure 5. The time integrated measurements of the beam cross section using radiachromic film indicate a more well defined central current spot with partial loss of the current halo that accompanied the wire grid cells. When one of the two crosses was replaced with a grid, the transport efficiency increased but remained below the wire grid level. These results suggest that each cross increases the maximum current transported in the tube, but is not quite as efficient in transporting the full current as a grid or foil would be.

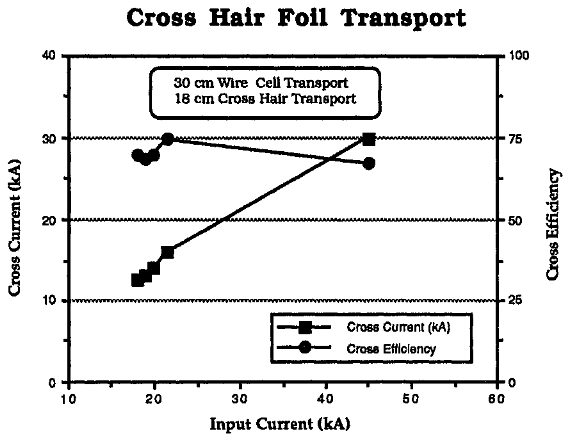

Figure 4 : Transport with the last two foils replaced by wire crosses.

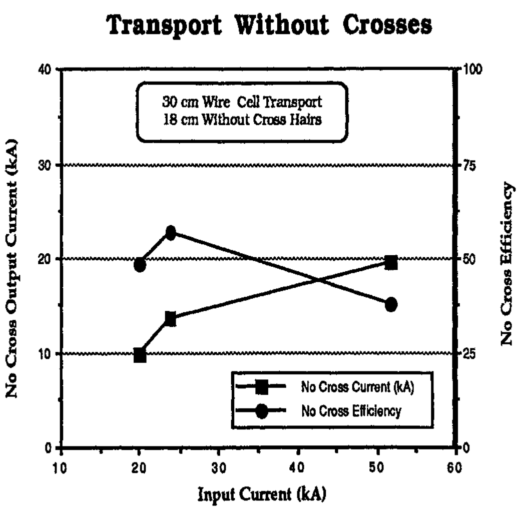

Figure 5 : Transport with the last two wire cells replaced with blanks.

Conclusions

Transverse conducting foils can transport high currents in vacuum, which are in excess of the longitudinal space charge limit. The foils permit stable transport of high current electron beams over distances many times the beam radius. One of the important effects that needs to be studied further is the amount of emittance growth resulting from this transport systems. The beam emittance seems to be the major factor determining the beam profile and transport efficiency. There are two major sources of beam emittance inherent in our experiments. The diode itself produces a beam with an emittance in the vicinity of 150 cm-mrad. In addition, the anharmonic nature of the electric field near the foils makes the foil a non-linear beam focusing element which heats the beam.

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